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Case study

Single stage concrete pumping through 2.432 km (1.51 miles): Weather and execution challenges

Chetan Hazaree [a,*], Viswanath Mahadevan [b,1]

[a] Hindustan Construction Company Ltd., Hincon House, 247 Park, LBS Marg, Vikhroli West, Mumbai 400 083, India[2]
[b] BASF India Limited (Construction Chemicals), C-406, MIDC, t.t.c., Turbhe, ASI/B/EB/T, Navi Mumbai 400 613, India

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ABSTRACT

This paper describes the execution challenges faced during single stage pumping of concrete through 2.432 km. Pump and pipeline selection and installation, materials' development, establishing of control points and controlling variations are discussed. Concrete responses to weather changes play a vital role in concreting and pumping methodology development. Measuring pump pressure during pumping can provide insightful guidance to concreting. In order to optimize concrete mixtures, distance-specific mixture designs were developed and a relation between air-free paste volume (AFPV) and pumping distance is derived. Pipeline priming and washout procedures specific to long-distance pumping are elaborated in detail. The paper presents a broad understanding regarding the challenges encountered; changes in pumping distance, materials, and climate would change the approach to solutions.

1. Introduction

Pumping of concrete is a globally practiced and established method of concrete conveying and distribution, but requires a delicate balance between materials and equipment. Reinforced by continual advancements in pump and concrete technologies, pumping to challenging heights and distances is becoming a possibility. Pumpability per-se is the ability of confined concrete to flow (to be mobilized) under pressure while maintaining its initial properties (Jolin et al., 2006; Gray, 1962). Some research studies dealing with this very practical problem of pumping have been reported but have offered limited understanding (Best and Lane, 1980; Browne and Bamforth, 1977; Chapdelaine, 2007; Kaplan and Denis, 2005; Kwon et al., 2013; Rio and Rodriguez, 2009; Sakuta et al., 1989). This paper describes field challenges pertaining to establishing control points, identification of reasons for blockages, equipment selection, materials development and weather while pumping through a distance of 2.432 km (1.51 miles). As an outcome of this practice study, a correlation between the paste content and pumping distance is drawn.

* Corresponding author. Tel.: +91 22 25751000x1273; fax: +91 22 25779570; mobile: +91 9930193045.
E-mail addresses: chetan.hazaree@hccindia.com (C. Hazaree), viswanath.mahadevan@basf.com (V. Mahadevan).
1 Tel.: +91 22 27629027; fax: +91 22 41577766; mobile: +91 9819438127.
2 www.hccindia.com.

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2. Long distance pumping of concrete (LDPC)

2.1. Envisaging LDPC

The specific critical task of a typical hydropower project discussed herein is part concrete lining of a 6.300 km long 3.76 m finished diameter Head Race Tunnel (HRT). Fig. 1 shows the schematic layout and the coaxial form used. The distances for lining included 1.360 km on upstream side and 2.432 km on the downstream side. Due to smaller diameter tunnel, vehicle movement is restricted, and simultaneous implementation of multiple activities is impossible as well as it involves occupational risks. An alternative way for conveying concrete was deliberated, and log-distance pumping of concrete (LDPC) was identified as a means of conveying and distributing of concrete.

Concrete lining in a tunnel is a 24-7, cyclical activity; the cycle time of which is determined by the concrete responses (sets, gains strength) in given conditions. In this project, the cycle time required stripping of formwork to commence approximately at 30 h after starting of concreting. The circular form length was 36 m (six panels, each of 6 m length). Forming stripping started at the starting point and sequentially proceeded further.

2.2. Control points

Pumping of concrete for such long distances depends on synergy of intricately dependent factors such as materials, machinery and plant, ambient climatic conditions, construction methodology and human resource. Apart from the materials' variations, developing holistic and robust mixture(s) needs accounting for possible span of construction (weather changes), working shifts, materials variations and skill level of the workforce. Fig. 2 shows a sampling of the key points that evolved as control points (CPs) while attempting this LDPC. At the planning stage itself, most of these factors were deliberated, anticipated and resorted fully. At times, it is not possible to anticipate such control points; full-scale field trials prove very insightful in highlighting such un-identified and un-anticipated issues.

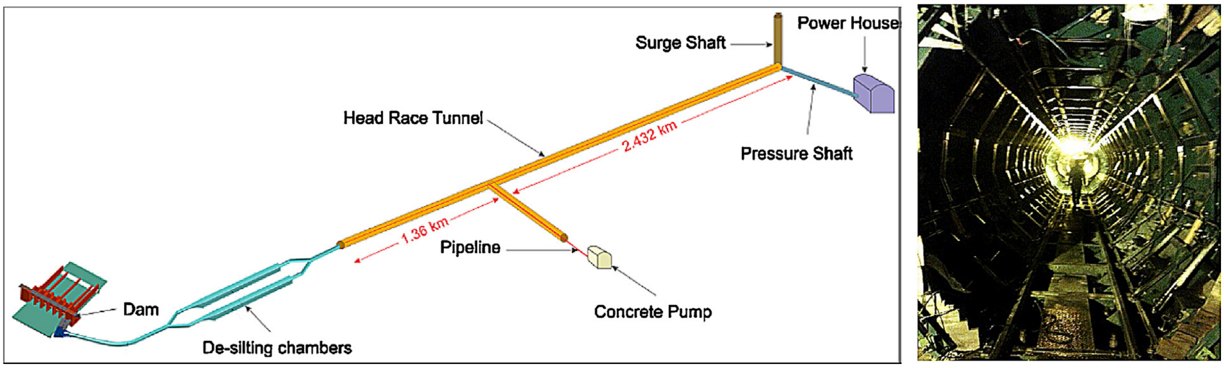

Fig. 1. Pumping scheme and lining form.

CP-1 Aggregate crushing & Screening plants	CP-2 Materials & batching plant	CP-3 Pumping point & pipeline	CP-4 Concreting at pouring point and finished concrete
• Feed control • Multiple crushers' control • Fines content • Consistent grading & shape	• Cement fineness • LOI & fineness of fly ash • Admixture formulation & regulation • Weather at batching plant • Production rate • Concrete flow & retention • Segregation, bleeding, visual stability • Temperature response & setting time • Routine QC checks	• Concrete flow and pumpability • Pumping rate and turn-around time • Pump pressure measurements • Adequate lubrication • Periodic and prompt maintenance • Pipeline leveling, alignment, cleaning • Safety during operations • Weather inside tunnel	• Admixture and temperature sensitivity • Regulated stiffening & early stripping • No formation of joints (monolithic) • Good finish • Regulated heat generation • No cracking/ water-tightness • Durable concrete

Fig. 2. Sampling of various control points (CPs).

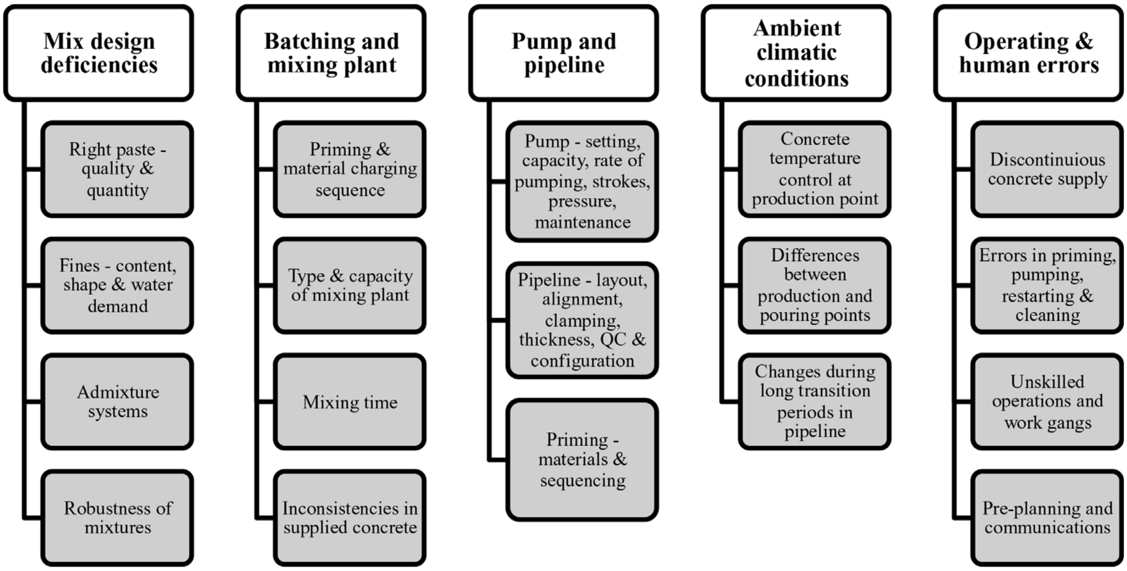

Fig. 3. Sampling of factors causing pumping blockages.

2.3. Pumping blockages

The materials development and specific responses to disruptions in pumping due to pump and pipeline blockages need to be discussed before commencing a LDPC project. Although test methods are devised to test specific aspects of pumpability of concrete, concrete pumping remains to date an empirical, trial and error process, involving frequent troubleshooting on construction sites (Kaplan and Denis, 2005). A qualitative and quantitative appreciation of the frictional resistance between the pipe and concrete along with commensurate paste requirements helps in proportioning the mixture. Full-scale trials are the best ways to resort to for establishing successful mixture designs. Blockages can be caused by many reasons (Fig. 3).

3. Pump and pipeline

3.1. Pump selection

Although advances in pump and concrete technologies are taking place, knowledge regarding translating a concrete mixture into a practically pumpable concrete remains more or less in the field, empirical and with few only. The challenges of pumping concrete through escalating heights and lengthier distances have not yet been fully investigated, theorized and documented. An example of this is the limitations that existing pump nomographs have. Selecting pumps based on knowledge of yester years and limited nomographs could be challenging and risky.

In the current case, the pump selection went through very serious deliberations. Eventually, based on the concreting requirements, pipeline diameter, pipe length, and layout and considering adequate tolerances, a pump with running parameters shown in Table 1 were selected. Head loss due to all possible number of bends, tapers and curvatures was accounted for the longest distance. Initially concrete with a slump ranging between 150 and 200 mm was designed and was conceived as "would be pumpable"; however, with initial failures to do so for long lengths, the concrete consistence was revised to flowable concrete. At this point it was realized that full scale trials would be necessary for finalizing the concrete mixtures.

Table 1
Pump parameters.

Parameter	Unit	Operating on	
		Piston side	Rod side
Max. number of strokes	Nos./min	14	21
Max. concrete pressure	bar	243	156
Max theor. concrete output	m^3/h	43	66
Pumping cylinder, dia × stroke	mm	180 × 2000	
Piston displacement, two cylinders	l	50.89	
Capacity of charging hopper	l	600	
Drive power	kW	330	
Driving speed	rpm	2100	

3.2. Pipeline configuration

Pipeline diameter is an important pumping length dependent factor in pump selection and overall design of pipeline circuit. For a fixed delivery rate, flow velocity increases with a decrease in pipe diameter. Moreover, larger diameter pipelines cause less resistance and hence pumps require lesser working pressure. Pumping length has an influence on the pipe diameter and normally for lengths longer than 200 m, a 150 mm diameter unit is used (Cooke, 1990). A practically relevant point is – larger diameter pipes are easier to clean. This project utilized a 150 mm diameter pipeline for full length.

Grade and thickness selection of pipelines depend on the working pressure and cylinder diameter (Cooke, 1990) of the pump and these factors decide operational safety as well. Higher working pressures near the pump necessitate thicker walls close to the pump; however, based on pressure calculations, pipe thickness can be reduced as the distance from pump increases. The wearing of pipeline is related to the abrasiveness of the concrete being pumped. A pipeline with lesser thickness would wear out faster (lower life expectancy) thus necessitating frequent replacements; a thicker pipeline might initially cost slightly more but will ensure a longer tenure before failure. Since hydropower projects are remotely located and concrete volumes are sizeable, selecting proper and adequate pipe thickness considering the volumes of concreting is vital. This project utilized reducing pipe thicknesses (14 mm, 10 mm and 7 mm) commensurate to the distance from pump. Juxtaposed with this is the fact that the self-weight of pipe and weight of concrete in the pipe, which, increases with the increase in its thickness and diameter of the pipeline (Fig. 4).

3.3. Pipeline installation

Careful, safe and fast pipeline installation for such long distances is an essential aspect of overall time management and productivity. Planning the installation of pipeline requires consideration to factors such as setting-up of pump, direction of pumping (in this case upstream and downstream), access to and space for cleaning the pipelines, anchoring and clamping arrangements (including quality), leveling and alignment of pipeline, routine quality control and planned maintenance.

As the resistance to concrete flow varies linearly to the pumping distance, any hindrance, change of direction, impediment created in the path of concrete would increase the back-pressure on the pump. Hence, it is essential to plan the layout of the pipeline with minimum possible bends, curvatures and tapers. The concrete properties also affect the pressure profiles of pump. The wearing in pipelines nearer to the pump is more than at the farther end. Logs kept for pipe location, QC checks and maintenance prove to be quite helpful.

Due to pulsation, the pump exerts a certain force on the pipeline due to which it jerks in a rhythmic manner. Higher the capacity of the pump, stronger are these jerks. To overcome, it is essential to have an immediate and solid support to the pipeline near the pump outlet. Fig. 5 shows a schematic sketch and actual laying. In addition to this as the pumping pressure increases (as pumping distance increases), the thrust on the pipeline also increases; hence sufficient anchoring is essential. There could be instances when a single blockage in the pipeline could exert so much force that it could potentially dislodge the pipe with anchor, and in the worst case such a vehement force would bend the pipe itself. Throughout this pumping exercise, the pipeline was firmly anchored with adequate packing until the pouring point. For safety reasons also, it was ensured that no pipe segment was unsupported.

Leveling of pipeline and its alignment (vertical and horizontal) prove to be crucial in reducing the pump backpressure. Small kinks originating at pipe joints, bends, and reducers, if properly straightened, could easily reduce the backpressure by 10–15 bars, which for long distances matter greatly. Another aspect of installation is choosing good quality clamps and seals; these should be commensurate to the grade, thickness and pressure sustaining capacity of the pipe. During periodic cleaning and maintenance, checking of seals and clamps (for water-tightness) is critical. Fig. 6 shows an example of rupturing of a joint seal, which leads to not only disruption of concrete pumping, but also escape from a major accident. The rupturing of

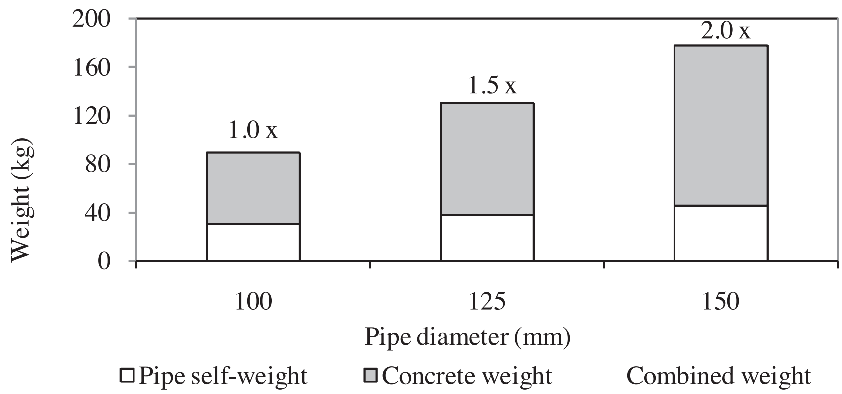

Fig. 4. Effect of pipe diameter (mm) on the handling weights (for a fixed pipe-length of 3 m).

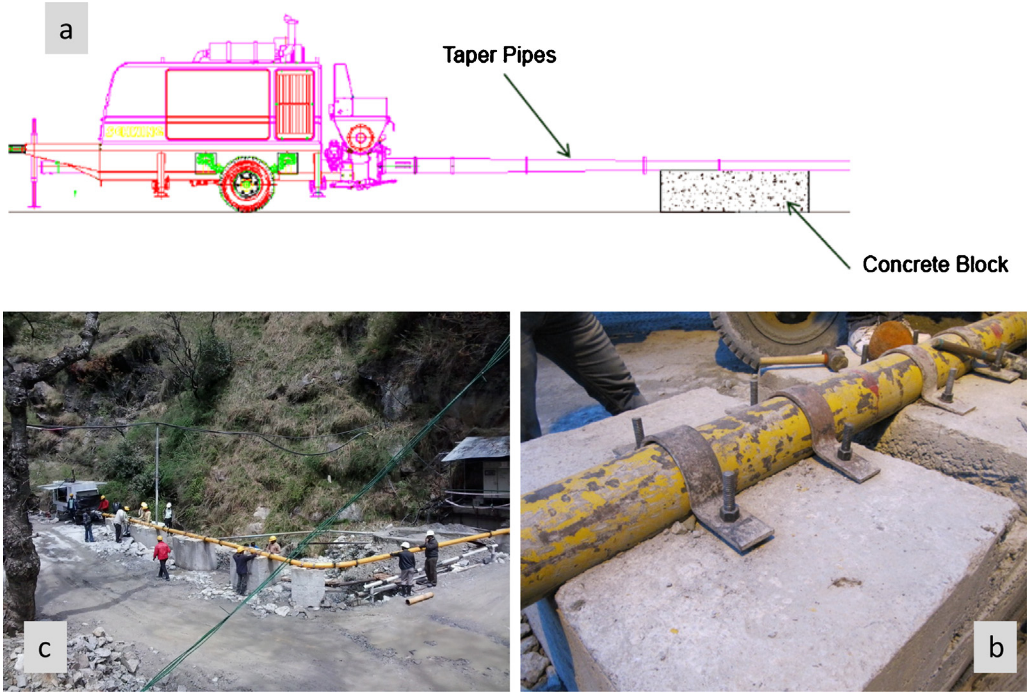

Fig. 5. Pipe support at pump outlet (a and b) and overall layout near the pump (c).

Fig. 6. Rupturing of seal causing disruption of pumping; drier concrete cylinder formation due to slurry leakage.

seal actually leads to escaping of water leaving behind the drier cement slurry and aggregates causing a blockage (cylinders shown in the Fig. 6), which in-turn builds up the pressure at that particular location.

During actual operations, sometimes, concrete is blocked in a particular location, which can be traced in two ways. First method is by sounding the pipeline with a hammer and second by observing the pump pressure. In either case, when a pipe section is to be opened, extreme care has to be taken to safely and meticulously open it, as sudden opening leads to release of built-up pressure. Clearing that section of pipeline and then re-fixing it with proper alignment and continuity are important tasks that require proper training.

4. Materials' development and control

4.1. Retention-risked volume-setting times

The desired output (hence feed) of the pump is a crucial factor in deciding the retention period of concrete (see Fig. 7). This retention period of concrete is a function of pipe diameter and the distance of pumping. The distance dependent retention period can be decided from a simplified equation of the form $y = mx + c$, however, a graphical representation helps guide the

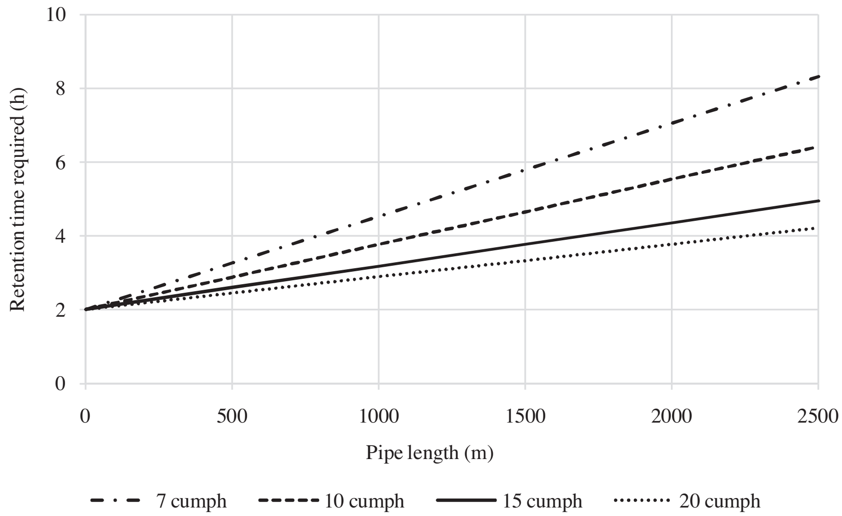

Fig. 7. Influence of delivery rate for a fixed diameter (150 mm) on retention time of concrete.

processes. The workability retention was designed taking into account a contingency time of around two hours in addition to the batching, transporting, and testing time requirements. This ensures safe cleaning and resumption of pipeline in case of disruption and/or any contingency during concreting. Moreover, the admixture selection should be guided by the possible extremes in the temperatures and other climatic factors that can potentially affect concrete performance. As far as possible, a single robust admixture should be targeted to meet all of these requirements. An additional retarder can be used provided regulated usage is practiced while being cognizant of the variations in the performance parameters of concrete. The designed mix should also take into account the workable range of pump pressures.

In LDPC, a significant volume of concrete is always at risk inside the pipeline. The volume of concrete and hence the gestation-period in pipeline (from pump to pouring point) proportionately increase with increasing pipe length and diameter and reduce with pumping rate. A pipe diameter of 150 mm requires a concrete volume of 0.18 m^3 per meter of pipe; therefore, for terminal distance (2.432 km), the risked volume of concrete was about 44 m^3. Considering the time cycle requirement of stripping the formwork approximately at 30 h, in order to having sufficient time for concrete to gain strength while balancing between the required pour time, the setting time was targeted to be around 18–20 h.

4.2. Required concrete characteristics

For developing concrete mixtures suitable LDPC, a set of parameters were developed based on time-cycle requirement, weather and pumpability requirements. These are summarized in Table 2. Multiple execution challenges exist while translating a concept into a reality. The challenge is in the right balance of equipments, materials, human resource and precisely blending these factors into a workable solution in a given environment. Following sections describe some of these challenges briefly.

OPC (specific gravity 3.15) conforming to IS 8112 (Bureau of Indian Standards (BIS), 2005) (Equivalent ASTM C150, American Society for Testing and Materials (ASTM), 2012) and a class F fly ash (specific gravity 2.1) conforming to IS 3812

Table 2
Summary of the targeted mix design characteristics.

Parameter	Minimum	Maximum
Flow (mm), season dependent	550	700
Type of concrete[a]	Flowable	Flowable
Final setting time (h) in lab	16	22
Pumping distance (m)	450	2500
Retention time (h)	4	12
Ambient temp. outside the tunnel (°C)	5	33
Ambient temp. inside the tunnel (°C)	25	45
Relative humidity inside the tunnel (%)	95	100
Stripping strength of concrete (MPa)	5	7
Characteristic strength (MPa)	25	–

[a] Homogeneous, non-segregating, enough paste, stable.

(Bureau of Indian Standards (BIS), 2003) (ASTM C618, American Society for Testing and Materials (ASTM), 2012) were used as binders. Crushed aggregates with 20 mm maximum size meeting IS 383 (Bureau of Indian Standards (BIS), 2002) (ASTM C33, American Society for Testing and Materials (ASTM), 2013) were used. A specially developed admixture conforming to IS 9103 (Bureau of Indian Standards (BIS), 1999) (ASTM C494, American Society for Testing and Materials (ASTM), 2013) was used along with use of a sugar-based retarder at times. A typical mixture for medium range distances (1.2–1.5 km) consisted of 340 kg OPC, 135 kg fly ash, 200 kg water, 948 kg coarse aggregate, 766 kg of fine aggregate and admixture varying between 2.4 and 5.2 kg per m^3. The observed flow at various admixture dosages was 600 ± 50 mm in lab initially, and final setting times 20 ± 1 h, 30 h compressive strength 1.07–4.31 MPa, 3-d compressive strength 19.05–28.56 MPa. As the project progressed, this mix design was altered to suit specific distance ranges and accordingly the paste contents were varied. The variation of paste content with pumping distance is discussed in one of the following sections.

4.3. Multiple crushers and sources

Typically, on medium to large sized hydropower projects, multiple sources for aggregate making materials are inevitable. Often, a blend of river boulder material (RBM), quarried material (QM) and blasted tunnel muck (BTM) is used to cater to the rather scattered and voluminous construction sites. Furthermore, using multiple aggregate crushers at multiple locations is common. RBM and BTM (which are being used in this project) have potentially higher variability than QM and could also result into products having higher variability, thus necessitating improved control over the crushers. Critical amongst the produced crushed aggregates is the fines fraction especially below 300 μm.

4.4. Lean supplier base

Restricting the sources of binders helps optimize admixture to a greater extent – often restricting it to a single component addition. Under some circumstances, it becomes essential to use an additional admixture component (for example a viscosity modifier or a retarder) to be able to use two or more sources of cements or combinations with supplementary cementitious materials. Hence, quality assurance considerations should ideally begin with addressing supply-chain issues.

5. Weather changes

Any construction activity that spans over several seasons should account for the climatic variations in its work-plan. There will be a definite impact of changes in the climatic conditions on the properties and performance of concrete and extra care is required in case of LDP. The workability (rheology) response of the concrete mixtures is the critical property affected by weather. The setting behavior and strength development are also affected; however in this case since the temperature and humidity at the placement point remained more or less steady and in a narrow window, the setting and strength were less affected.

The differences and the variations between the external (concrete production point) and internal (i.e. at gantry) climates cause substantial changes in the behavior of concretes. This is because the concrete goes through changes as it moves through long distance pipe. Periodic performance trials and measurements at the production and placement points are essential. The transitions in temperature and humidity need to be carefully monitored along with specific responses of concrete viz. workability, retention, setting behavior, etc.

5.1. Supply-line profiles

Fig. 8 shows an example of temperature and humidity profiles. Measurement of such profiles helped proportioning the dosages of admixtures and in selecting the right mixture. Temperature and humidity profiles help in anticipating possible changes in the concrete properties and pumping pressure regimes. The difference between the ambient weather at the production point and at the pouring point is crucial as a larger difference can cause concrete to go through a transition that the lab trials do not exhibit. Temperature differences up to 28 °C and humidity differences up to 70% were tackled in the project.

5.2. Concrete responses

Even though the materials and equipment remain the same, concrete properties are dramatically affected by the ambient temperature. Such changes in concrete in response to ambient weather conditions impact pump performance and concreting in-turn. Fig. 9 shows the effects of ambient climate on concrete properties by extracting examples from one day each in summer and winter. The upper graph (a) shows the difference in measured slump flow value between the batching plant (B/P) and the pumping point (P/P). While the lower graph (b) shows the wait time required for the transit trucks before the concrete could come to a long-distance pumpable flow. Following observations are relevant:

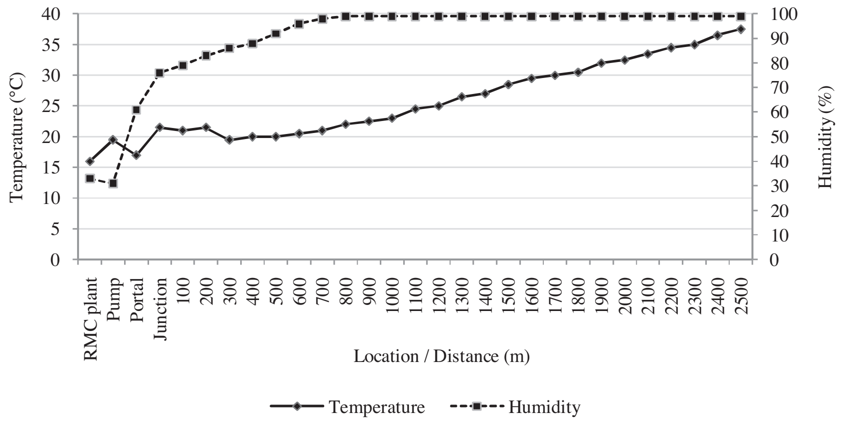

Fig. 8. Temperature and humidity monitoring profiles along the tunnel length (an example).

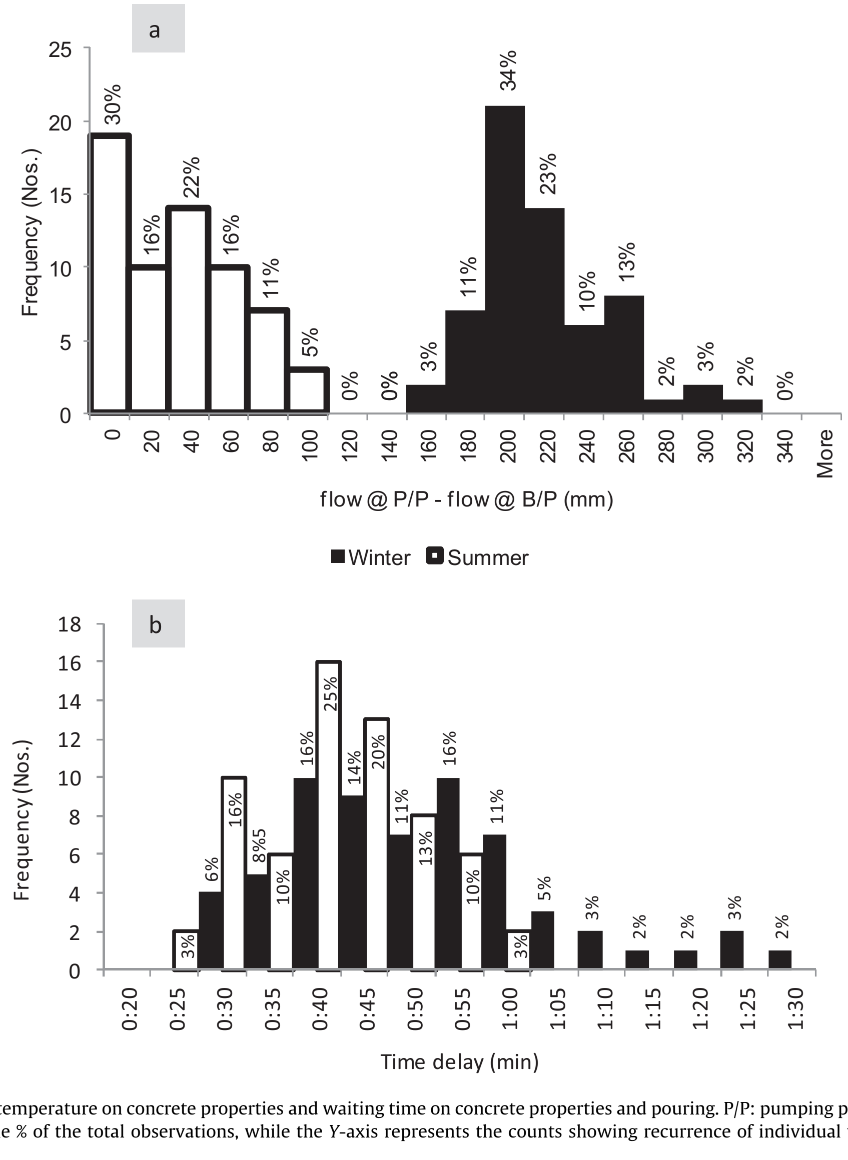

Fig. 9. Typical effects of temperature on concrete properties and waiting time on concrete properties and pouring. P/P: pumping point, B/P: batching plant. The data labels show the % of the total observations, while the *Y*-axis represents the counts showing recurrence of individual values (frequency).

i. In summer, in majority of the cases, the flow of concrete at batching plant is almost at its maximum for a given mix design and required no further opening of concrete. The rate of chemical reactions is faster and hence the admixture dispersion and reaction starts early taking the concrete to maximum possible flow valve. On the contrary, in winter, due to decelerated reactions, the concrete mixtures opened up slowly and often at much lower consistence. There were occasions when a mixture that showed flow behavior demonstrated a slump behavior at batching plant. The graphical representation shows that in summer, majority of concrete reached maximum flow, while in winter, due to slower rate of reactions, majority of concrete batches had much lower flow value batching plant were much lesser
ii. Since the winter temperature retards the chemical reactions, inhibiting the dispersion of admixture and hence opening of the flow of concrete, the concrete mixing time in winters was kept almost 10–15 s more than in summer. Even with extended mixing times, the reactions could not be practically and usefully accelerated to suit the intended purpose.
iii. Another implication of weather and speed of reaction is the stand-by time required for concrete to become pumpable commensurate to required flow values. This is shown in Fig. 9(b). The stand-by or waiting time for transit mixers was more in winter, since the concrete took time to reach pumpable workability. This affects the cycle times and often necessitated engaging more transit mixers in winter than in summer. The travel time between batching plant and pumping location (ready for pumping) was on an average 25 min. The graphical representation indicates that the wait time in winters was both longer than in summers.
iv. Since the temperature and humidity at the placement location remained more or less steady, the setting and strength development of concrete at the gantry location remained practically unaffected.

6. Pumping of concrete

6.1. Priming – a critical transitional step

Priming or lubricating of pipes is a critical transitional step, wherein empty pipes gradually get fully filled with concrete. The primary objectives of priming are (i) to keep the aggregate particles in suspension and impede their counterproductive advancing; (ii) to keep the concrete–steel interface coated with a film of grout, while sealing minor gaps and (iii) to prevent pumped concrete from drying and helping plug formation. Successful priming depends on the grout mix, concrete mix, pumping rate, pipeline layout, priming methodology adopted and the piston cylinder volume. If not properly understood and executed, blockages at priming stage are quite common even during normal pumping.

In case of long-distance pumping, this step becomes more critical – primarily because tracing blockages are tedious, demoralizing and can cause disproportionate damage. Multiple grout mixtures were tried initially. Finally, the adopted grout mixture contained 645 kg/m^3 of cement and fly ash, w/cm ratio 0.38 and admixture 7.1 kg/m^3 and occasionally retarder was used at 2.5 kg/m^3. It is worth noting that grout without admixture was difficult to pump and retarder was used mostly on the downstream side where higher temperatures were potentially dropping the workability. Few iterations were tried for estimating accurate grout volume, which was just sufficient to coat the entire pipeline properly. An important point while commencing pumping actual concrete is to ensure complete emptying of pump hopper of the grout. This avoids problematic mixing of grout and concrete.

In one of the instances, while pumping concrete in the upstream direction, it was becoming difficult to pump 20 mm down mixture directly behind the priming grout. Two primary reasons were identified for this viz. excess quantity of grout being pumped before pumping concrete and breaking of transition zone between the grout and concrete. The pressurized concrete coming from behind looses coarse aggregate fraction to the grout due to pulsation. As coarse aggregates are heavier these settle down and pile up at a location or a stretch completely breaking the transition zone. As the piling up continues a jam of coarse aggregates (with some fines) is created, through which slurry escapes in the forward direction leading to blockage and pressure built-up. To overcome this problem, an alternative methodology was adopted, wherein; the grout was followed by mortar, 10 mm down mix and then the main concrete. This is pictorially depicted in Fig. 10. By adopting this methodology progressively thicker (more viscous) material is introduced in the pipeline.

6.2. Concrete pumping – various effects

6.2.1. Measurements – samples

The pump pressure development was used as a continuous monitoring tool in every pour for smooth concrete pumping, anticipating changes, possible disruptions and blockages. The measured pressure was the maximum pressure shown on the dial gauge and not the pulsation. For longer distances, the maximum pressures developed were higher and reduced as the pumping distance reduced. For a pour, as the concrete travels through the pipeline, the pump back-pressure increases, reaches a peak and then remains more or less stable during the complete pour. Minor fluctuations in the pressure take place due to various reasons. Fig. 11 shows the pressure–volume profiles for two pumping distances.

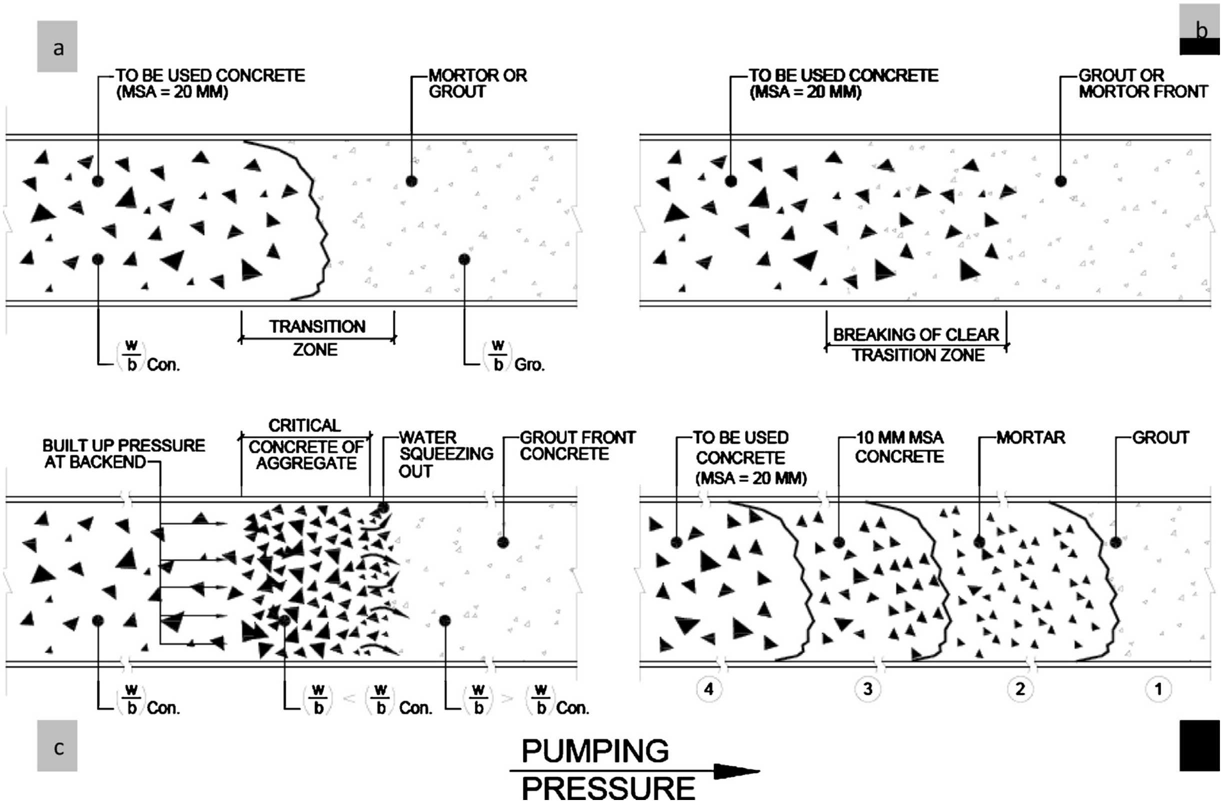

Fig. 10. Understanding the problem with priming (a–c) and the solution (d).

6.2.2. Effect of season on pumping

As discussed before, the ambient temperature at which concrete is manufactured influences the fresh properties of concrete. This in-turn also changes the perception regarding the pumpability of concrete even after using hot water. Following are critical observations:

i. With reduction in ambient temperature, the consistencies of grout and concretes reduced. With lower temperatures, the admixture took almost 30–75 min more to show a similar to normal temperature behavior. During winter it often reflected in holding transit mixers for longer time for the flow to reach safe pumpability value.

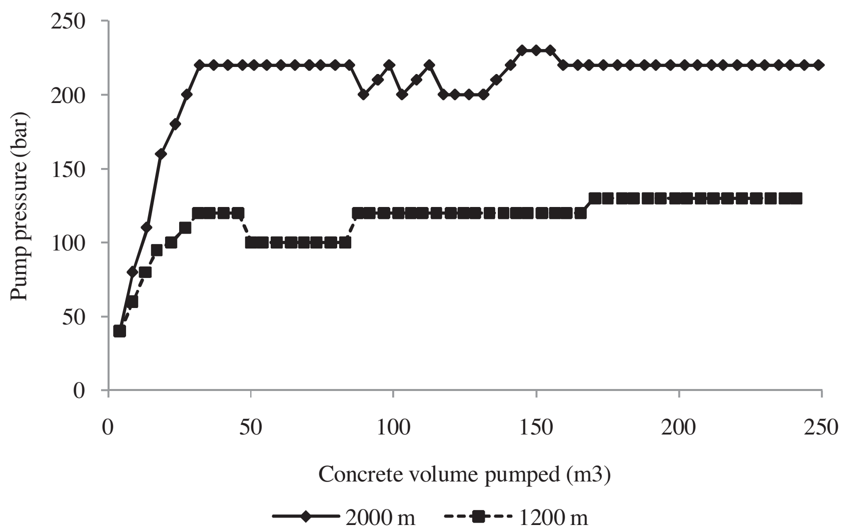

Fig. 11. Pump pressure as function of pumped concrete volume for two distances.

ii. Reduced flow values of concrete in winter in-turn reflect on the average peak pump pressures, which for similar distances were higher by approximately 20–50 bar than the corresponding pressures in summers for equivalent length.
iii. Caution was exercised regarding bleeding while pumping concretes in winter. Instances of mixtures bleeding at much lower slump flow values were quite common. These mixtures did not show any bleeding during normal working temperatures. Marginal and acceptable bleeding can be used in pumping as long as the mixture remains homogeneous and there are no segregation and settlement.

6.2.3. Anticipating choking

It is important to anticipate blockage during pumping and the pumping pressure measurements prove very useful in predicting possible upcoming blockage. Fig. 12 shows two such examples. The normal range of operating pressure for a given mix and a range of distance remains more or less constant and is shown in the figure as a function of volume of concrete pumped. However, if the pump pressure crosses that normal range, then a problem can be anticipated. In the shown figure, Failure-1 took place because of an abrupt bend in two straight pipe segments (at 1600 m from pump), which lead to blockage at that location, eventually culminating into disruption of concreting. In the Failure-2, concreting was going on smoothly, until some leakage in the pipe segment (at 370 m from pump) leads to loss of slurry and blocking of pipe. The blocked pipe segment was removed, cleaned and reinstalled, the pump back-pressure resumed normalcy. The pressure built-up helps in guiding the tracing of blockage; a gradual built-up indicates blockage at longer distances from pump, while abrupt peaking of pressure indicates blockage nearer to the pump.

6.2.4. Distance – paste correlation

For a mix to be pumpable for a certain distance under a given climatic (temperature) conditions, the paste has to fulfill minimum paste requirements – both qualitatively and quantitatively. Although in the reported work, the paste quality was not quantified, the minimal quantity was definitely quantified. Fig. 13 shows the air-free paste volume (AFPV) of mixtures used for various distances. As the concrete moves under pressure through the pipeline, depending on the consistency of concrete, admixture type and ambient climatic conditions, the air in the concrete is reduced. Hence the paste content taken into account is the air-free paste content.

Initially no such a chart was available; this chart evolved as the work progressed. For two segments there were only two mixtures; each was used since the tunnel was not day-lighted on one side. The paste volumes were more-or-less optimal for given distances under given circumstances. At these pressures, the pump was operating without any issues (excess pressures) and with no or rarely occurring blockages. Similar profiles can be developed for distance-pump pressure and can be used for guidance purposes. The paste-volume–distance chart will be a function of the pipeline configuration (diameter, bends, joints, tapers, level), materials, mixing method and the ambient weather. Of these factors, the layout and weather were crucial in this case. As experienced, it is very crucial for the mix designer to appreciate the quantum of pressure that concrete mixtures are exposed to. While being drawn in the piston and while

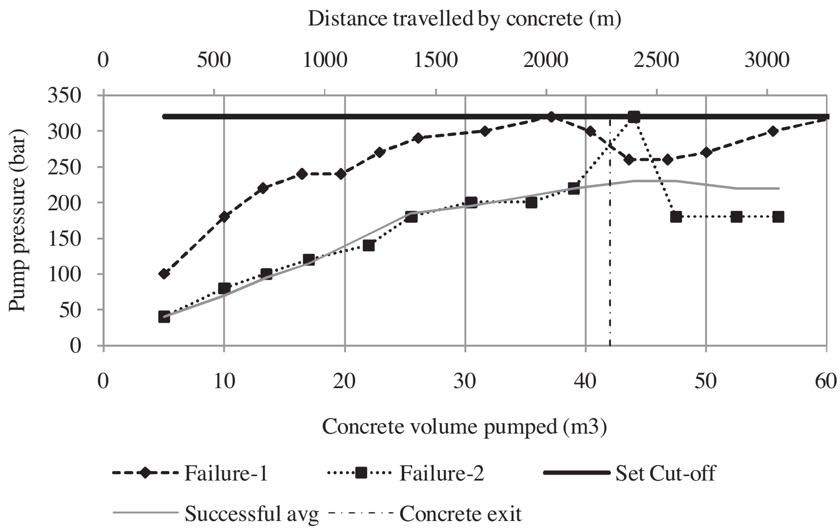

Fig. 12. Pump pressure as a function of pumped concrete volume for two failure events.

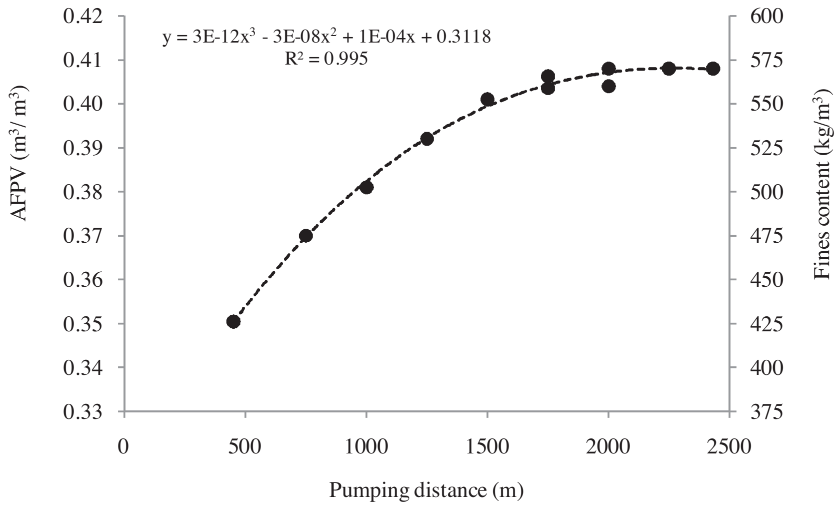

Fig. 13. Distance – paste (binders) correlation.

experiencing the strokes, the concrete properties should remain more or less unchanged, which is the crux of the whole effort.

6.2.5. Cleaning of pipeline

Achieving safe, efficient and least wastage cleaning of concrete pump and pipeline without causing blockages and any manual interference is a task requiring training, skills and coordination. Cleaning for LDPC is done before and after pouring and is usually accomplished with water. Cleaning with compressed air can be resorted to, but only in multiple small stretches. Air cleaning causes serious safety concerns and arranging of electric power supply is a challenging task for long and small diameter tunnels.

Washout, i.e. water cleaning while concluding pumping requires preliminary calculations regarding the concrete volume required for completing the pour for the concrete remaining in the pipeline to be usefully evacuated. Wastages are inevitable if this is not well-attended. While water cleaning, a separating plug is inserted between the concrete and the pressurized water. The plug could be an assembly of hard sponge cleaning balls, hard sponge pigs and blow-out ball (also called as go-devil). The plug ensures immiscibility of water in concrete, leakages in which could cause blockages during post-pour cleaning. Since there is a high risk of concrete depositing along the length of the pipeline, go-devil and pigs are especially used. Any deposited concrete has the potential to disrupt pumping. Depending on the pipe-length to be cleaned and hence the water pressure that is exerted on the plug, a shunted assembly of cleaning balls, pigs and go-devil is required to be applied. Fig. 14 shows an example used for maximum distance.

Fig. 14. Post-pour wash-out assembly of balls and go-devil.

7. Further development

This paper described some of the challenges faced while adopting LDPC methodology. During the course of this development, some of the gaps noticed in the existing body of knowledge that need further development in regard to are summarized below:

i. Pump nomographs – developing pump nomographs for longer distances for deciding pump pressure as a function of concrete consistency and pipe diameter is one of the foremost needs. The consistency requirements for LDP appear to be different than those for routine distances. Both these issues need to be studied and investigated further. For example, the author is now investigating pumping concrete for 7 km.
ii. Prediction of pumpability for longer distances – albeit there are tribometers being developed and a field rheometer (Kasten et al., 2009) has also been devised, the accuracy and field applicability of such equipments for LDP is yet to be clearly established. What is more interesting is the temperature dependent anomalous behavior of concrete. The measurement of index workability characterizing properties could be misleading; moreover the correlation of these properties with pump pressure is an essential next step in developing the knowledge. Since performing full scale trials is expensive, but resorting to some inexpensive, accurate and discretionary methods is very much required.
iii. Distance specific consistency of pumpable concrete – defining the windows of consistencies for long-distance pumpable concrete is becoming more critical. Higher consistence concretes require lesser pressure for pumping and this fact is critical as savings in pressure enhance pump life and reduce risk. This fact needs to be carefully evaluated with the wear and tear of the pipe life.
iv. Grout mixtures and priming are two critical transitional steps, as well as the operation and materials related know-how are quite decisive in successful pumping. In general it would be helpful to have guiding mixtures and correlations between grout consistencies and their ability to coat a fixed length of pipeline. Apart from right mixture proportioning, moderated or excessive grout volumes both are potentially risky. Estimating grout quantity requires knowledge about the pump circuit including pipe length, slope, bends, curvatures, changes in the levels and the concrete to be pumped.
v. Paste volume–distance diagrams – such diagrams need to be developed for various distances as these can answer multiple questions. Moreover, it will be of great practical help if the paste quality can be characterized in a very simplistic and practically usable manner.

8. Summary

i. Successful long-distance pumping requires meticulous planning and establishing proper synergy between materials-equipment-weather-manpower. Equipment, pipeline and materials selection and characteristics are crucial along with setting up of right control points. Methodology should be robust and responsive while judicially balancing with weather.
ii. Suitable priming, pumping and closing methodologies (ball passing, water cleaning, etc.) should be carefully evaluated and pre-tested before undertaking LDP. Careful, weather dependent measurements of concrete properties and correlating with ambient weather help in developing proper controls and risk mitigation strategies.
iii. Developing paste-distance, binders-distance correlations, specific to a pump and pipeline configuration gives insightful guidance in optimizing concrete mixtures.

References

American Society for Testing and Materials (ASTM). ASTM C150 Standard specification for portland cement. West Conshohocken, PA, USA: ASTM International; 2012.
American Society for Testing and Materials (ASTM). ASTM C33 Standard specification for concrete aggregates. West Conshohocken, PA, USA: ASTM International; 2013.
American Society for Testing and Materials (ASTM). ASTM C494 Standard specification for chemical admixture for concrete. West Conshohocken, PA, USA: ASTM International; 2013.
American Society for Testing and Materials (ASTM). ASTM C618 Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. West Conshohocken, PA, USA: ASTM International; 2012.
Best JF, Lane RO. Testing for optimal pumpability of concrete. Concr Int 1980.
Browne R, Bamforth P. Tests to establish concrete pumpability. ACI J Proc 1977;74(May (5)):193–203.
Bureau of Indian Standards (BIS). IS 3812:2003 pulverized fuel ash – specifications. New Delhi, India: Bureau of Indian Standards; 2003.
Bureau of Indian Standards (BIS). IS 383:1970 specifications for coarse and fine aggregates from natural sources for concrete. New Delhi, India: Bureau of Indian Standards; 2002.
Bureau of Indian Standards (BIS). IS 8112:1989 43 grade ordinary Portland cement specifications. New Delhi, India: Bureau of Indian Standards; 2005.
Bureau of Indian Standards (BIS). IS 9103: concrete admixtures – specifications. New Delhi, India: Bureau of Indian Standards; 1999.
Chapdelaine F. Fundamental and practical study on pumping of concrete.. (Ph.D. thesis) Quebec, Canada: Laval University; 2007.. (in French).
Cooke TH. Concrete Pumping and Spraying. London, UK: Thomas Telford; 1990.
Gray J. Laboratory procedure for comparing pumpability of concrete mixtures. In: Sixty-Fifth Annual Meeting of the Society. June 24–29; Washington, DC: National Crushed Stone Association; 1962. p. 964–71.
Jolin M, Chapdelaine F, Gagnon F, Beaupre D. Pumping concrete: a fundamental and practical approach. In: Morgan DR, Parker HW, editors. Shotcrete for Underground Support X. ASCE; 2006.

Kaplan D, de Larrard F, Sedran T. Avoidance of blockages in concrete pumping process. ACI Mater J 2005;102-M21:183–91.
Kasten KJ. Gleitrohr – Rheometer Ein Verfahren zur Bestimmung der Fließeigenschaften von Dickstoffen in Rohrleitungen.. (Ph.D. thesis) Germany: TU Dresden; 2009.
Kwon SH, Park CK, Jeong JH, Jo SD, Lee. SH. Prediction of concrete pumping: Part I – Development of new tribometer for analysis of lubricating layer. ACI Mater J 2013;110(6):647–55.
Rio O, Rodriguez A. On the real time assessment of pumping mixes under actual or quasi actual conditions. In: 3rd RILEM Symposium on Rheology of Cement Suspensions such as Fresh Concrete. 19–21 August; Reykjavik, Iceland: RILEM; 2009. p. 97–104.
Sakuta M, Kasanu I, Yamane S, Sakamoto A. Pumpability of fresh concrete. Takenaka Technical Research Laboratory; 1989.